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FlowCyl: one-parameter characterisation of matrix rheology

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Abstract: The FlowCyl is a simple flow viscometer – a modification of the Marsh Cone test apparatus developed to characterize cement pastes and grouts. The FlowCyl gives a one-parameter characterisation of rheology called the flow resistance ratio or λ_Q for use in the Particle-Matrix concrete proportioning Model (PMM) as a description of the viscous phase of the concrete, while another parameter related to packing density is used to describe the particle phase. There have been numerous studies which have shown how the matrix λ_Q values affect the rheological parameters of concretes with a given particle system. Recent studies have shown that the FlowCyl test, which has previously proven acceptable for the one-parameter characterisation of matrix phase rheology, is probably not suitable for matrices with high powder content and a superplasticiser dosage below the surface adsorption saturation. This paper reviews current studies that compare the measurements of the FlowCyl with the results obtained using a rheometer and presents initial results from a series of simulations of the FlowCyl test conducted to analyse the effect of yield shear stress (according to the Bingham model) on the measured flow resistance ratio λ_Q.

Keywords: *Rheology, matrix, FlowCyl, yield stress, plastic viscosity*

1. INTRODUCTION

1.1. The Particle-Matrix Model (PMM)

To simplify the practical modelling of the effect of different concrete part materials on concrete workability, Ernst Mørtsell developed a material model called the Particle-Matrix Model (PMM) as a part of his doctoral thesis at the Norwegian University of Science and Technology in 1996 [1]. According to the PMM philosophy, the workability of concrete depends on the properties of two phases: the fluid matrix phase (≤ 0.125 mm) and the solid particle phase (> 0.125 mm), *i.e.* a liquid phase (matrix) and a friction material (particles):

- The lubricating concrete **matrix phase** is defined as consisting of all fluids (water, admixtures, etc.) and particles (binder, filler, fines from the aggregate, etc.) ≤ 0.125 mm. This definition was chosen to acknowledge that under a given size, the behaviour

of particles will depend much more on their surface properties than on gravity or shape. This is particularly true when the particles are dispersed in water. It is therefore natural to let the small particles and entrained air by definition belong to the matrix;
- The **particle phase** dispersed in the lubricating matrix is defined as all the particles in concrete > 0.125 mm, which are in general the aggregate particles.

In practice, the PMM approach is based on a single-parameter characterisation of each phase, *i.e.* the flow resistance ratio of the matrix and the air voids modulus of the particles:

- The **flow resistance ratio** (λ_Q) is determined in the FlowCyl test, which is a simple flow viscometer – a modification of the Marsh Cone test apparatus (see in [1] and [2] for details);
- The **air voids modulus** (H_m) is based on the air voids space ratio of the fine (0.125-4 mm) and coarse (> 4 mm) portions of the particle system. Details on the determination of this parameter can be found in [1] and [2].

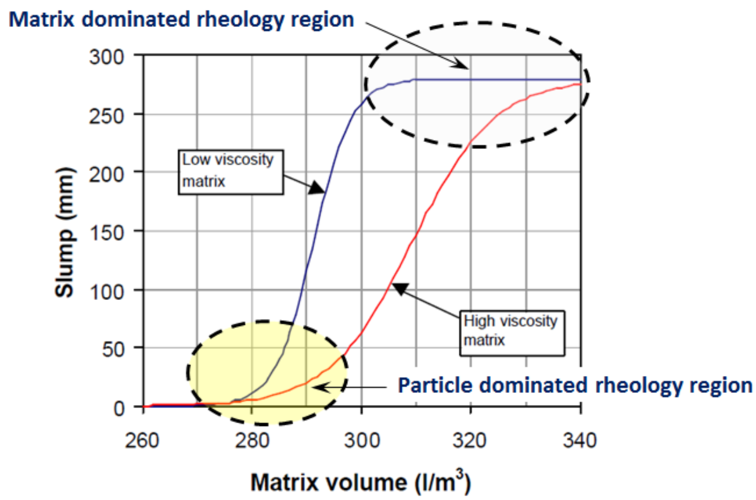

Figure 1: The slump (or possibly another rheological parameter) workability function for two concretes based on the same particle system, but different matrix compositions [3].

Mørtsell [1] demonstrated that, when the properties of the two phases are determined in this simple way, the workability of the concrete depends on these properties and the volume ratio between them. The workability of the concrete as characterised by the slump and flow measure (or another rheological parameter) is then finally expressed as a function of the flow resistance ratio of the matrix, the air voids modulus of the particle phase, and the volume fraction of the matrix. Mørtsell [1] chose the hyperbolic tangent (tanh) function as a basis for his workability function, which then resembles an "S-shape" in matrix volume vs. slump (also slump-flow, yield stress or any other workability parameter) coordinates (Figure 1). The syntax and use of these functions are described in detail in [1] and [2].

1.2. Experimental setup: FlowCyl

The FlowCyl (Figure 2b and Figure 2c) is a modification of the Marsh cone test apparatus (Figure 2a), which is workability test equipment originally developed to characterise oil well cements [1], but also applied for the specification and quality control of other types of cement pastes and grouts [4], [5].

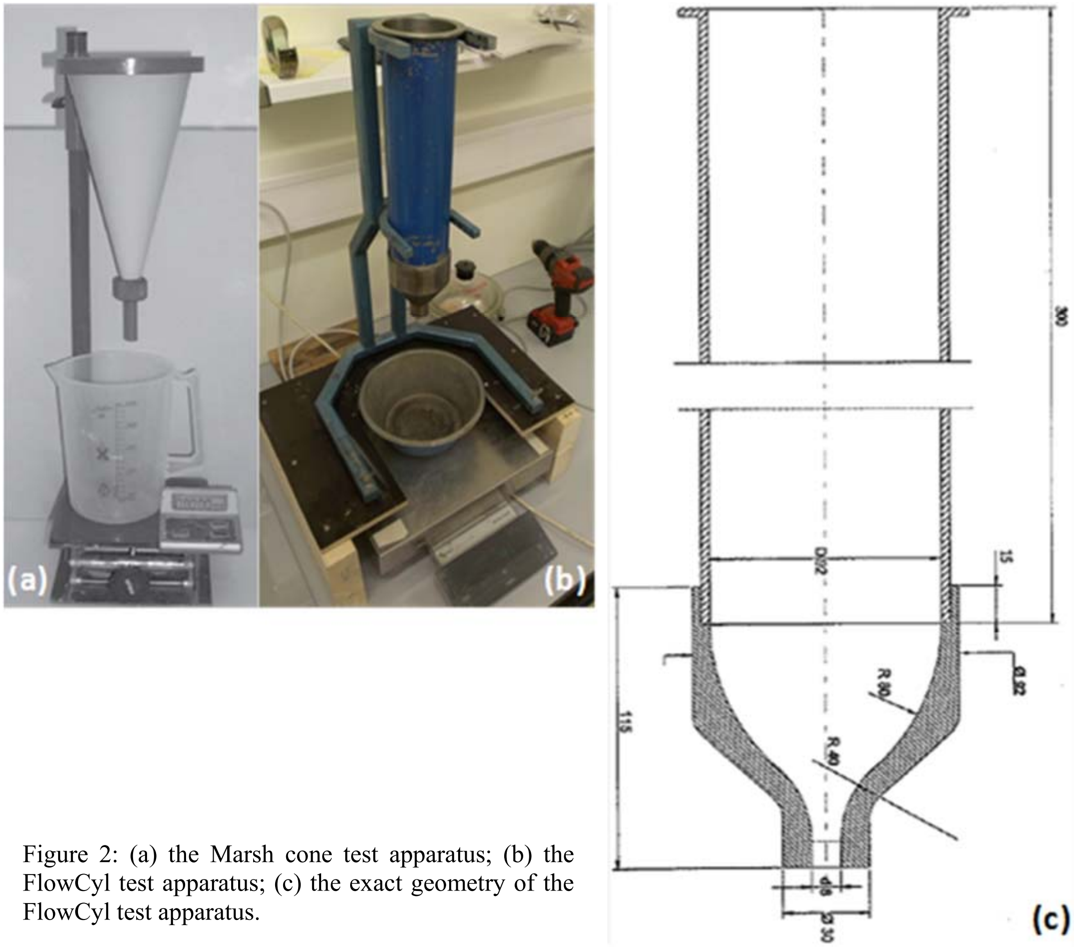

Figure 2: (a) the Marsh cone test apparatus; (b) the FlowCyl test apparatus; (c) the exact geometry of the FlowCyl test apparatus.

As shown in Figure 2, the original cone of the Marsh Cone (Figure 2a) has been replaced in the FlowCyl by a cylinder ending in a V-funnel with a narrow nozzle outlet (Figure 2b and Figure 2c) [1]. During a measurement, the FlowCyl is placed vertically in a rack with a steel bowl on an electronic scale connected to a computer underneath (Figure 2a). The FlowCyl is filled with the matrix up to the level of 15 mm below the top edge while the outlet is closed. Then the outlet is opened and the weight increase of the bowl is recorded continuously (sampling rate 2 sec) to characterise the flow. Mørtsell [1] deduced a unit-less single parameter, the flow resistance ratio (λ_Q), from the flow measurements. This is defined as the difference in flow rate between the test material (matrix) and an "ideal" fluid [1] with no internal flow resistance and no external cohesion or friction. It is given by the expression:

$$\lambda_Q = F_t / F_i \,, \tag{1}$$

where
F_t = average difference between the theoretical flow rate of an "ideal" fluid and the measured flow rate of the tested matrix; and
F_i = the average flow rate of the "ideal" fluid.

By definition [1], the "ideal" fluid has a λ_Q value of 0.0, while the theoretical upper limit of the λ_Q value for a viscous fluid is 1.0. Further details on the FlowCyl test method and the mathematical derivation of λ_Q can be found in [1], [2], [6].

1.3. Rheological models and measurements vs. FlowCyl

Ernst Mørtsell showed in his doctoral thesis [1] that the PMM is applicable for conventional (vibrated) normal-weight Norwegian concrete mixes with consistencies of up to about 250 mm of slump, based on natural sand and matrices with relatively low fines content. Later, Smeplass [2] demonstrated that the PMM is also applicable to light-weight aggregate concrete (LWAC) based on natural sand and coarse lightweight aggregates, *i.e.* no modifications are required to handle the reduced density of the LWAC.

Smeplass and Mørtsell [6] investigated the applicability of the PMM to self-compacting concrete (SCC). Their study included both high-strength SCC based on high-strength ordinary Portland cement (OPC) without additional fillers and low-strength SCC based on regular OPC with substantial filler additions. The w/p ratio (water/powder ratio, including filler $\leq$ 0.125 mm) was kept constant for both groups of mixes in the range of 0.31-0.37, while the w/b ratio (water/binder ratio, filler $\leq$ 0.125 mm excluded) was 0.40 for the high-strength and 0.60 for the low-strength SCC. A co-polymeric superplasticiser was used at a dosage of 1.0% to 1.5% of the weight of the cement. The air voids modulus, *i.e.* the composition of the particle phase, was kept constant for all the mixes. The hypothesis for the study was that the PMM would work even better with the matrix-dominated SCC mixes, and that the workability of the SCC mixes tested would be a unique function of the flow resistance ratio of the matrix and the volume of the matrix according to the PMM. However, the results revealed that, to achieve a slump-flow measurement of approx. 650 mm, the necessary matrix volume was 40-80 l/m^3 lower for the mixes based on the high-strength OPC than for the regular OPC mixes, when all other parameters (including λ_Q values) were comparable. In other words, the researchers did not find a simple correlation between the flow resistance ratio of the matrix (λ_Q) and the workability of the SCC. Smeplass and Mørtsell [6] proposed that the problem was in the measuring device used for the characterisation of the matrix, *i.e.* the FlowCyl. They suggested that the problem with the FlowCyl was that it gives only a single value, whereas the matrix is at least a two-parameter fluid that needs to be more fundamentally described with a yield value (τ_0) and plastic viscosity (μ).

In a follow-up study to the work done by Smeplass and Mørtsell [6], Hammer and Wallevik [7] used a coaxial cylinder viscometer ConTec Viscometer 4 to measure the matrix rheology instead of the FlowCyl, and a coaxial cylinder viscometer BML to characterise the rheological properties of the equivalent concrete mixes. Both viscometers (*i.e.* the ConTec Viscometer 4 and the BML) were able to measure the consistency in terms of yield value and plastic viscosity. The matrix and corresponding concrete compositions were similar to those used by Smeplass and Mørtsell [6] and based on the same two cement types. The conclusion of the study [7] was that the reliability of predicting concrete consistency from equivalent matrix rheological parameters is weakened by the fact that different cement types respond differently to water-reducing admixtures. In other words, their results indicated that a given matrix consistency (characterised by the yield and plastic viscosity parameters) does not always give one and the same independent concrete consistency for a given particle phase. They also suggested that one reason for this variation in concrete workability could be due to the different interactions of the cements with the superplasticiser (SP) molecules. They suggested that the dosage of SP used (0.4% to 0.8% of the cement weight) was probably too low to disperse the cement particles to the same degree in mixes with the different cement types and that well-dispersed cement systems could be expected to give a better correlation between matrix and concrete consistency. However, the study of Hammer and Wallevik [7] measured the matrices with a ConTec Viscometer 4, which is essentially designed to be used for mortars and may not be able to represent the actual rheological behaviour of the matrix in full-scale concretes. This is because of the large measurement gap compared to the actual spacing between the aggregates. More details on this problem are provided in Ferraris and Gaidis [8]. Furthermore, it has been demonstrated that preparation of the paste in a Hobart mixer, as done in the study by Hammer and Wallevik [7], does not resemble the actual shear rates observed for the matrices during the mixing of the corresponding full-scale concrete mixes [9] and [10]. This is due to the presence of aggregate particles, which have a pronounced effect on the particle dispersion in matrices with SPs, and consequently on the rheology.

The other studies of interest for understanding the actual fundamental rheological meaning of the FlowCyl measurements in the light of the PMM are those by Pedersen and Mørtsell [11], Cepuritis [3] and Kjos-Hanssen [12], [13]. In these studies, the FlowCyl measurements on matrices with a relatively high content of crushed sand filler were carried out in parallel using a rheometer. Pedersen and Mørtsell [11] used a FANN-coaxial cylinder viscometer for matrices at three different w/c ratios, 0.40, 0.50 and 0.60, and at three different w/p ratios, 0.31, 0.38 and 0.43. All the mixes had different aggregate fillers and water-reducing admixtures. They found that the λ_Q measurements correlated very closely with the plastic viscosity measurements through a power law (R^2=0.9830). The Bingham's yield stress of the matrices tested varied in the range of -1[1] to 6 Pa. Cepuritis [3] studied a range of matrices with very different crushed sand fillers at a fixed w/c ratio of 0.5, variable w/p ratios, and a fixed content of SP at 0.6% of the cement weight. An Anton Paar MCR 300 rheometer with a bob-in-a-cup geometry was used for the measurements in parallel with the FlowCyl, and again a good linear relationship was found between the plastic viscosity measurements and the flow resistance ratios determined (R^2=0.9162). The Bingham's yield stress of the matrices tested varied in the range of 7 to 26 Pa. Another similar study using the same test set-up as Cepuritis [3] was done by Kjos-Hanssen [13]. Once again a very close correlation was reported between the flow-resistance ratios and the plastic viscosities measured. Cepuritis [3] also found that once the shape and mineralogy of the crushed aggregate filler material and the SP dosage was fixed, the impact of the crushed fines on the paste workability in terms of λ_Q could be very precisely described by the specific surface area of the crushed fines. However, Kjos-Hanssen in [12], [13] was only able to replicate this observation once the dosage of the SP was increased up to a certain level and the potential effect from the yield stress was reduced, otherwise the reported specific surface values would correspond to higher λ_Q values than expected. This indicates that there might be a variable degree of contribution from yield stress on the flow resistance determined, depending on the composition of the matrix tested (its SP dosage).

These last conclusions from the studies by Kjos-Hanssen [12], [13] can be further examined in the light of the studies by Roussel and Le Roy [4], [5], who have elaborated on the option of using the Marsh cone test apparatus (Figure 2a) as a viscometer for cement paste to determine the rheological parameters of Newtonian and Bingham fluids. The studies [4], [5] have shown that it is possible to use the Buckingham-Reiner equation for Bingham material in a cylindrical tube (Equation (2)) to derive an analytical solution to the flow time of a cement paste of known yield stress τ_0 and plastic viscosity μ using the Marsh Cone apparatus. The Equation (2) below prevails if the inertia effects are assumed to be negligible, and the flow is assumed to be equal to zero at the fluid/ cylinder interface.

[1] Of course, a negative Bingham's yield stress value is not meaningful from a physical perspective. However, it can occur when the shear stress corresponding to a zero flow rate is extrapolated from the best-fit line obtained during linear regression of the experimental flow-curve data from the viscometer.

$$Q = \frac{\pi A R^4}{8\mu}\left(1 - \frac{4}{3}\left(\frac{2\tau_0}{AR}\right) + \frac{1}{3}\left(\frac{2\tau_0}{AR}\right)^4\right), \quad (2)$$

where
Q = rate of flow;
A = pressure gradient motor of the steady-state flow (dp/dx);
R = cylinder radius.

Equation (2) shows that when the yield stress of a cement paste is negligible or non-existent, or the shear on the flowing fluid is so high that there is no plug-flow, the registered rate of flow (and the flow time) would be reduced to Poiseuille's Law and would thus be inversely proportional to the plastic viscosity of the fluid tested. From the results of calibration of their analytical model, Roussel and Le Roy [4], [5] concluded that the apparent viscosity of cement paste whose behaviour can be approximated by a Bingham law is difficult to assess using the Marsh cone. This is because the flow time becomes strongly affected by plastic yield stress values higher than 20 Pa, while the correlation to viscosity has been successfully validated for pure Newtonian fluids.

1.4 Objectives of the paper

The discussion in Section 1.3 above raises a very important question: Why doesn't the FlowCyl test on matrices reflect the differences in concrete workability for all types of concrete, even when the particle phase is kept constant? One of the steps in the direction of answering this question is to get a better understanding of to what extent the yield stress of the matrix affects the flow resistance ratio values. This paper reports some preliminary results on the development of a numerical model of the FlowCyl, as well as a series of simulations of the FlowCyl test aimed at analysing the effect of the yield shear stress (according to the Bingham model) on the flow resistance ratio λ_Q.

For this purpose, we chose experimental results on matrices similar to those in the studies by Kjos-Hanssen [12], [13], and in particular where the SP dosage was 0.75% of the cement weight, which we anticipated on the basis of practical experience would to be enough for surface adsorption saturation with the given admixture (*i.e.* not quantified by actual SP adsorption). The experimental results on matrices similar to those in [12], [13] are given in Figure 3 and show that once the assumed SP surface adsorption is achieved, there is indeed a close correlation between the Bingham's plastic viscosity and the flow resistance ratio. Furthermore, the Bingham's parameters are interrelated. So we decided to perform numerical FlowCyl simulations on matrices, where some of the plastic viscosities from Figure 3b are coupled with yield stresses, which are both larger and smaller than those experimentally measured (essentially data points falling in the red area in Figure 3b). This would allow us to see whether such matrices would also result in numerical λ_Q values that deviate from the relationship shown in Figure 3a, *i.e.* fall in the red area depicted.

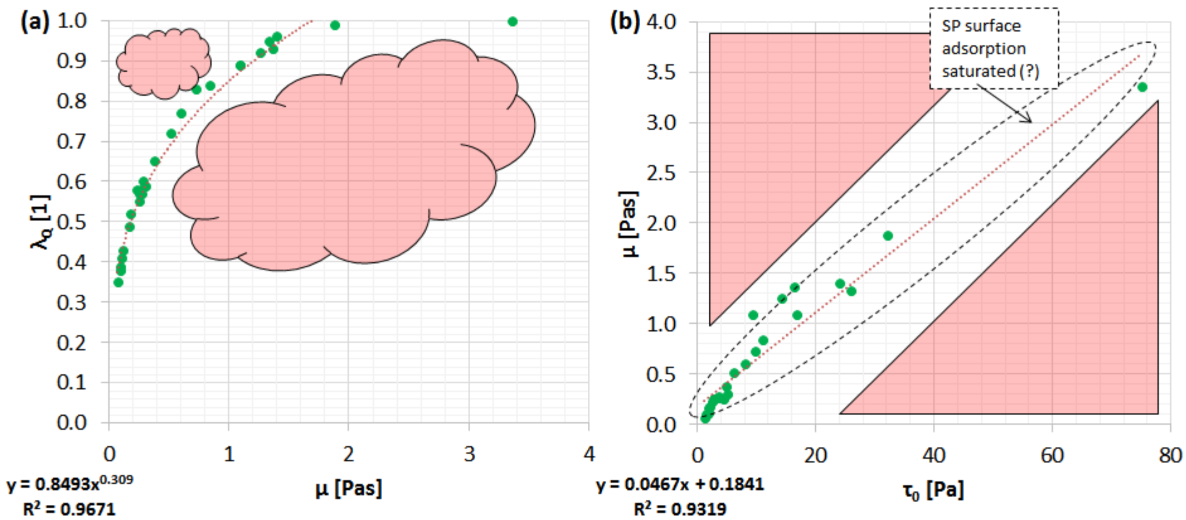

Figure 3: Correlation between the Bingham's rheological parameters and the flow resistance ratios determined for the matrices tested (the matrix composition was similar to those in [12], [13], with an SP dosage of 0.75%).

Figure 4:Initial condition for the CFD model.

2. NUMERICAL SIMULATIONS

In recent decades, computational fluid dynamics (CFD) simulations have been successfully used to understand concrete flow phenomena such as flow through reinforcement [14], [15] and gravity-induced aggregate migration [16], [17]. The setup, validation, and results of the CFD model developed to simulate the FlowCyl are presented in the following sections.

2.1 Model setup

The CFD model was developed in Flow3D, commercial analysis software that uses the finite volume method to discretise the mass and momentum conservation equations needed to find the pressure and velocity fields inside the FlowCyl. The free surface of the cement paste was tracked using the volume of fluid method [18], which is one of the most accurate interface tracking procedures [19]. Figure 4 illustrates the initial condition for the CFD model. The internal boundaries in the FlowCyl were modelled with a no-slip condition and the cement paste outflow was monitored by tracking the remaining volume in the simulated domain instead of measuring the mass in a bucket underneath the FlowCyl, as in the experiment.

2.1 Procedure

The flow behaviour of the cement paste matrices was simulated using the Bingham material model, and the flow resistance ratio (λ_Q) was calculated from the CFD model simulations. First, the volume change in the domain was recorded every two seconds to replicate the experimental measurements (see Section 1.2). The two-second volume loss was converted to the mass loss using a density of 1930 kg/m^3. Then, the mass loss over time was used to describe the flow rate of the simulated material. Finally, the difference between the flow rate of the simulated material and the flow rate of the "ideal" fluid was used to calculate the flow resistance ratio using Equation (1) just as in the calculation described for the experimental model in Section 1.2.

2.2 Model validation

Initially, the CFD model was used to simulate the flow in the FlowCyl for five of the experimentally tested cement paste matrices to investigate the performance of the model. Table 1 presents the experimentally found Bingham parameters and λ_Q alongside the numerically predicted λ_Q. The results show that the numerical model is able to predict the λ_Q of the matrices within 10% accuracy, which can be considered an acceptable precision for a numerical model.

Table 1: Experimentally found Bingham parameters and λ_Q, and numerically predicted flow resistance ratios.

Bingham Parameters		Experimental (FlowCyl) flow resistance ratio, λ_Q	Numerical (Flow-3D) flow resistance ratio, λ_Q	Deviation
τ_0 [Pa]	μ [Pas]			
2.643	0.233	0.580	0.607	5%
4.848	0.384	0.651	0.712	10%
6.134	0.517	0.722	0.776	8%
11.039	0.843	0.836	0.871	4%
16.453	1.367	0.935	0.921	-1%

2.3 Results

After validating the CFD model, we used it to simulate combinations of yield stress and plastic viscosity that lay off the diagonal in Figure 3b in order to investigate whether such combinations would result in a different relationship between the plastic viscosity and flow resistance than the one presented in Figure 3. Table 2 presents the various combinations of yield stress and plastic viscosity tested. Figure 5 shows the numerically predicted flow resistance ratio for the various combinations plotted as a function of the yield stress and plastic viscosity The results show a trend similar to the one in Figure 3a and that the flow resistance is primarily dominated by the plastic viscosity. The reason for this can be found in the fact that the flow resistance is governed by the flow condition at the outlet of the FlowCyl. The numerical model predicts shear rates of ~200 s^{-1} at the outlet. At such high shear rates, the apparent viscosity μ_{app} (the viscosity shown by the cement paste matrix) is highly dominated by the plastic viscosity in the Bingham material model and there is no plug-flow. This can be illustrated by the following examples where the apparent viscosity is calculated for three cement pastes at a shear rate of 200 s^{-1}. The three cement pastes have the following rheological properties: 1) τ_0 = 5 Pa and μ = 0.5 Pas; 2) τ_0 = 7.5 Pa and μ = 0.5 Pas; and 3) τ_0 = 5 Pa and μ = 0.75 Pas.

1. $\mu_{app} = \tau/\dot{\gamma} = \tau_0/\dot{\gamma} + \mu = 5/200 + 0.5 = 0.525$ Pas;
2. $\mu_{app} = \tau/\dot{\gamma} = \tau_0/\dot{\gamma} + \mu = 7.5/200 + 0.5 = 0.538$ Pas;
3. $\mu_{app} = \tau/\dot{\gamma} = \tau_0/\dot{\gamma} + \mu = 5/200 + 0.75 = 0.775$ Pas.

The above examples show that a 50% increase in the yield stress (from 5 Pa to 7.5 Pa) only makes the apparent viscosity increase by ~2%, whereas a 50% increase in the plastic viscosity (from 0.5 Pas to 0.75 Pas) makes the apparent viscosity increase by ~50%. So this could be the reason why the flow resistance ratio primarily depends on the plastic viscosity of the materials in the FlowCyl.

Table 2: The various combinations of yield stress and plastic viscosity used in the FlowCyl simulations. The entries marked with ♦ represent the combinations from the experimental study.

(τ_0; μ)	1	2	3	4	5	6
1	-	-	1.19;1.37	6;1.37	11;1.37	16.45;1.37 ♦
2	-	-	1.19;0.84	6;0.84	11;0.84 ♦	16.45;0.9
3	-	1.19;0.52	3.5;0.52	6.13;0.52 ♦	11;0.5	16.45;0.5
4	1.19;0.38	3;0.38	4.85;0.38 ♦	6.13;0.3	11;0.07	16.45;0.07
5	1.19;0.23	2.64;0.23 ♦	4.85;0.2	6.13;0.07	-	-
6	-	2.64;0.07	4.85;0.07	-	-	-

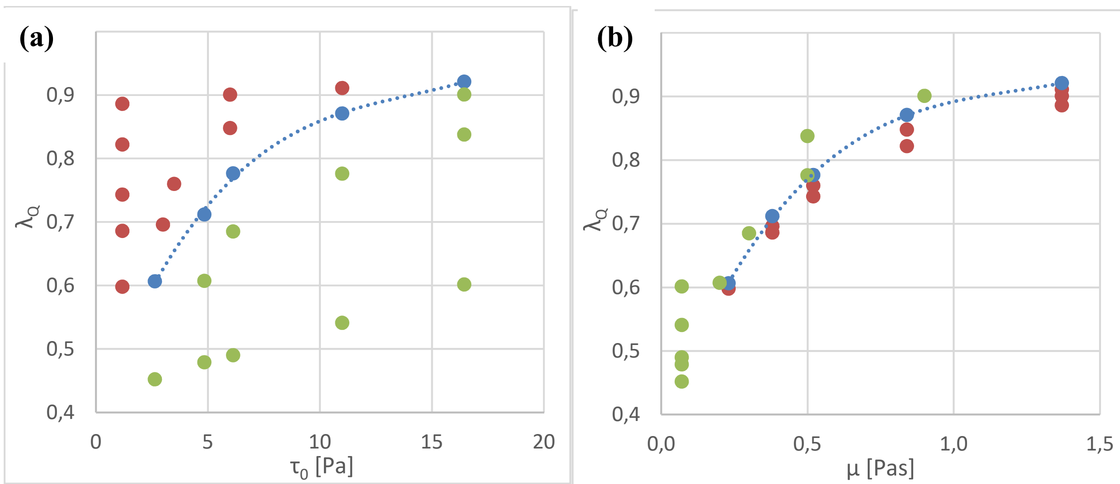

Figure 5: The flow resistance as a function of the yield stress (a) and plastic viscosity (b).

3. CONCLUDING REMARKS

The flow resistance ratio, as measured by the FlowCyl equipment, seems to be dominated by the plastic viscosity of the cement paste matrices in the range investigated. However, the plots shown in Figure 5 suggest that if the plastic viscosity becomes very low from a practical perspective (in this case, equal to 0.07 Pas, see Table 2) the variation of the yield stress (in this case, in the range of 2.64 Pa to 16.45 Pa, see Table 2) may have a relatively larger impact on the flow resistance ratios measured. So perhaps the numerical study should be broadened in future research to investigate more data points in the region where the plastic viscosities fall below about 0.25 Pas.

Whether the flow resistance ratio can be used as a single parameter to describe the flow behaviour of concrete matrices needs further investigation, based on the results obtained using the numerical model. From the studies discussed in this paper, it seems that the usefulness of the flow resistance ratio in predicting the flow behaviour of concrete might depend on the shear rates that the cement paste matrix undergoes during a given flow situation. The results of the numerical simulation indicate that the flow resistance is a good measure if the shear rates are relatively high.

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